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TRMM/LIS and GLM Lightning Optical Energies

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Overview

- General Comments
- Relationships Between Fundamental Quantities
- Analysis of OTD & TRMM/LIS Measurements
- Metrics
- Comparisons
- Trends

General Comments

Incident Energy is a Very Small Fraction of Flash Energy

- *E*: Flash Energy (GJ) is huge and is dissipated by acoustical waves, radiation, thermal conduction, & convection (mixing)

- radiation: radio, microwave, IR, visible, UV, X-Ray, gamma

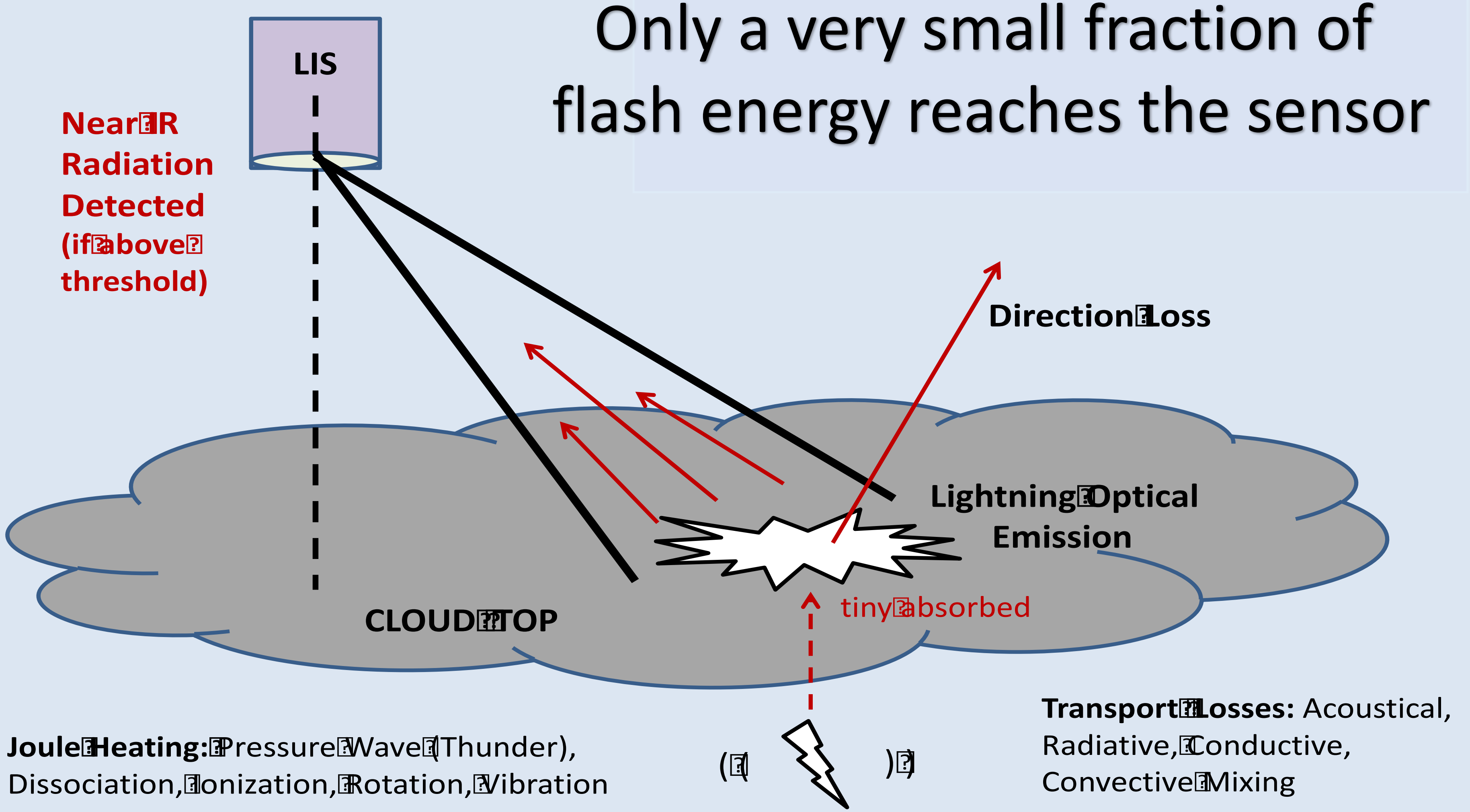
- near IR Flash Optical Energy emitted through 4π steradians

- *Q*: Incident Flash Optical Energy (~hundred or hundreds of fJ, depending on sensor) = energy of the sliver (< 4π) of multiple-scattered near IR photons incident on sensor. **$Q/E \sim 10^{-22}$**

- *Q**: The portion of *Q* converted to digital counts = *Q* minus losses (reflections, lens absorption, CCD quantum efficiency) and then converted to photoelectrons –> voltage –> digital counts.

Energy Flow

Only a very small fraction of flash energy reaches the sensor



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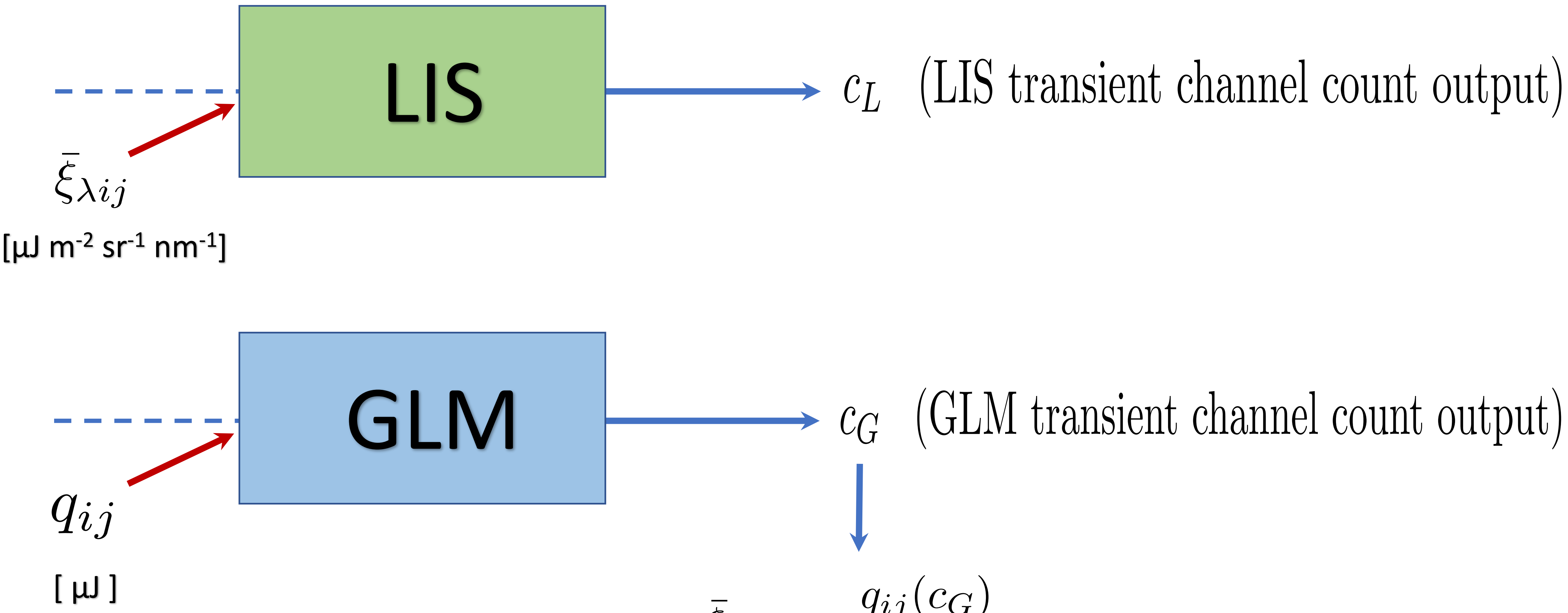
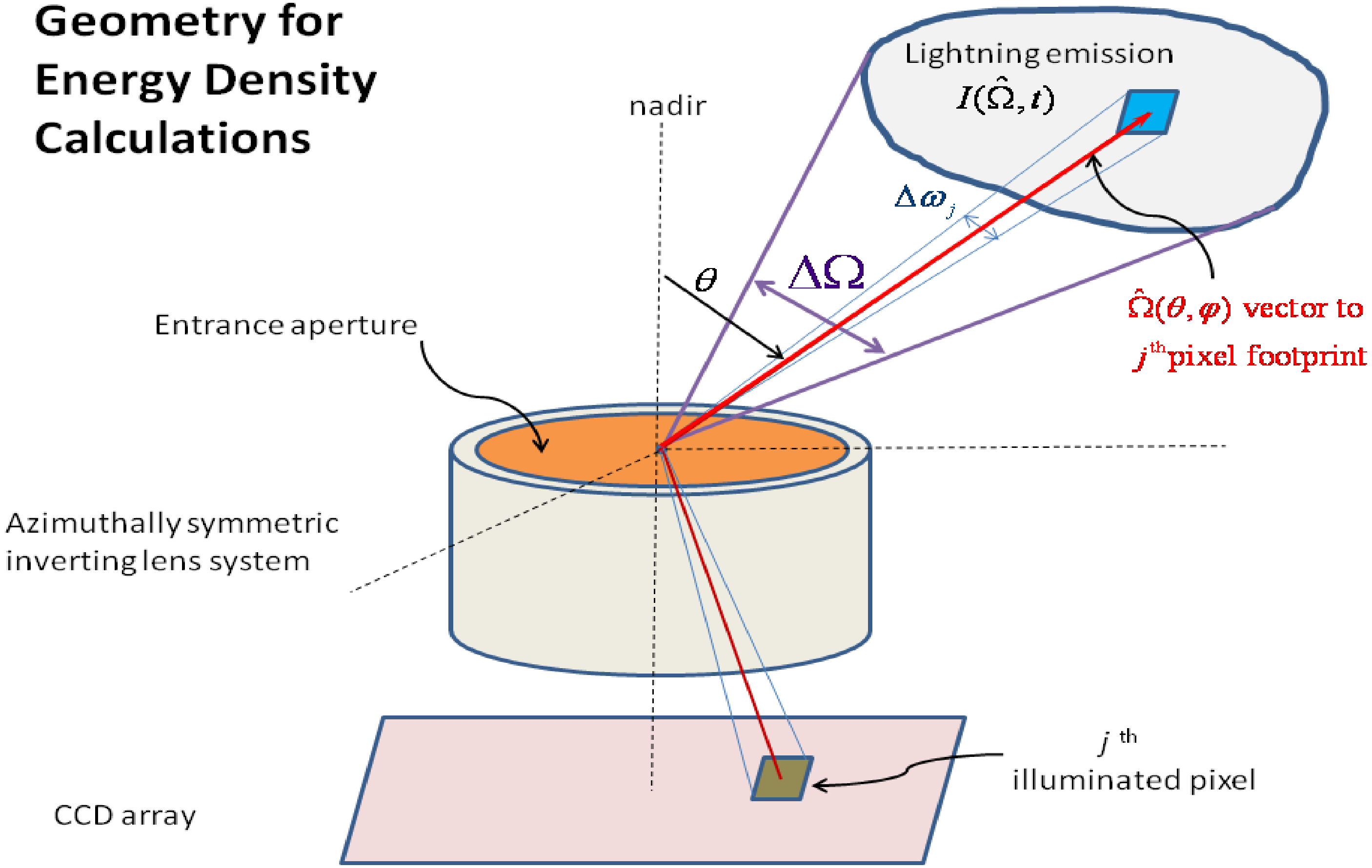


$$\bar{\xi}_{\lambda ij} = \frac{q_{ij}(c_G)}{A\Delta\lambda\Delta\omega_j}$$

$$Relationships\ \ Between\ \ Fundamental\ \ Quantities$$

$$\left(\left\langle \xi_\lambda(\hat{\Omega})\right\rangle,\ \ q^*_{ij},\ \ \Phi_\lambda\right)$$

Geometry for Energy Density Calculations



Front Lens Incident solid - angle - averaged spectral energy density (in $\mu J\ m^{-2} sr^{-1} \mu m^{-1}$) :

$$\left\langle \xi_\lambda(\hat{\Omega}) \right\rangle = \frac{1}{\Delta\Omega} \int_{\Delta\Omega} \int_{t_o}^{t_m} I_\lambda(\hat{\Omega}, t) dt d\Omega$$

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$$\left\langle \xi_\lambda(\hat{\Omega}) \right\rangle = \frac{1}{\Delta\Omega}\int_{\Delta\Omega}\left[\int_{t_o}^{t_m} I_\lambda(\hat{\Omega},t)dt\right]d\Omega = \frac{1}{\Delta\Omega}\int_{\Delta\Omega}\left[\sum_{i=1}^{m}\int_{t_{i-1}}^{t_i} I_\lambda(\hat{\Omega},t)dt\right]d\Omega = \frac{1}{\Delta\Omega}\int_{\Delta\Omega}\left[\sum_{i=1}^{m}\xi_{\lambda i}(\hat{\Omega})\right]d\Omega$$

$$= \frac{1}{\Delta\Omega}\sum_{i=1}^{m}\left[\int_{\Delta\Omega}\xi_{\lambda i}(\hat{\Omega})d\Omega\right] = \frac{1}{\Delta\Omega}\sum_{i=1}^{m}\left[\sum_{j=1}^{n}\int_{\Delta\omega_j}\xi_{\lambda i}(\hat{\Omega})d\Omega\right] = \frac{1}{\Delta\Omega}\sum_{i=1}^{m}\sum_{j=1}^{n}\Delta\omega_j\bar{\xi}_{\lambda ij} \simeq \frac{\Delta\omega}{\Delta\Omega}\sum_{i=1}^{m}\sum_{j=1}^{n}\bar{\xi}_{\lambda ij}$$

Hence:

$$\boxed{\left\langle \xi_\lambda(\hat{\Omega}) \right\rangle \simeq \frac{1}{n}\sum_{i=1}^{m}\sum_{j=1}^{n}\bar{\xi}_{\lambda ij}}$$

Solid Angle Averaged Spectral Energy Density

(in $\mu J\ m^{-2} sr^{-1} \mu m^{-1}$)

where:

$i = 1, ..., m$ ($m =$ # frames covered by the flash)

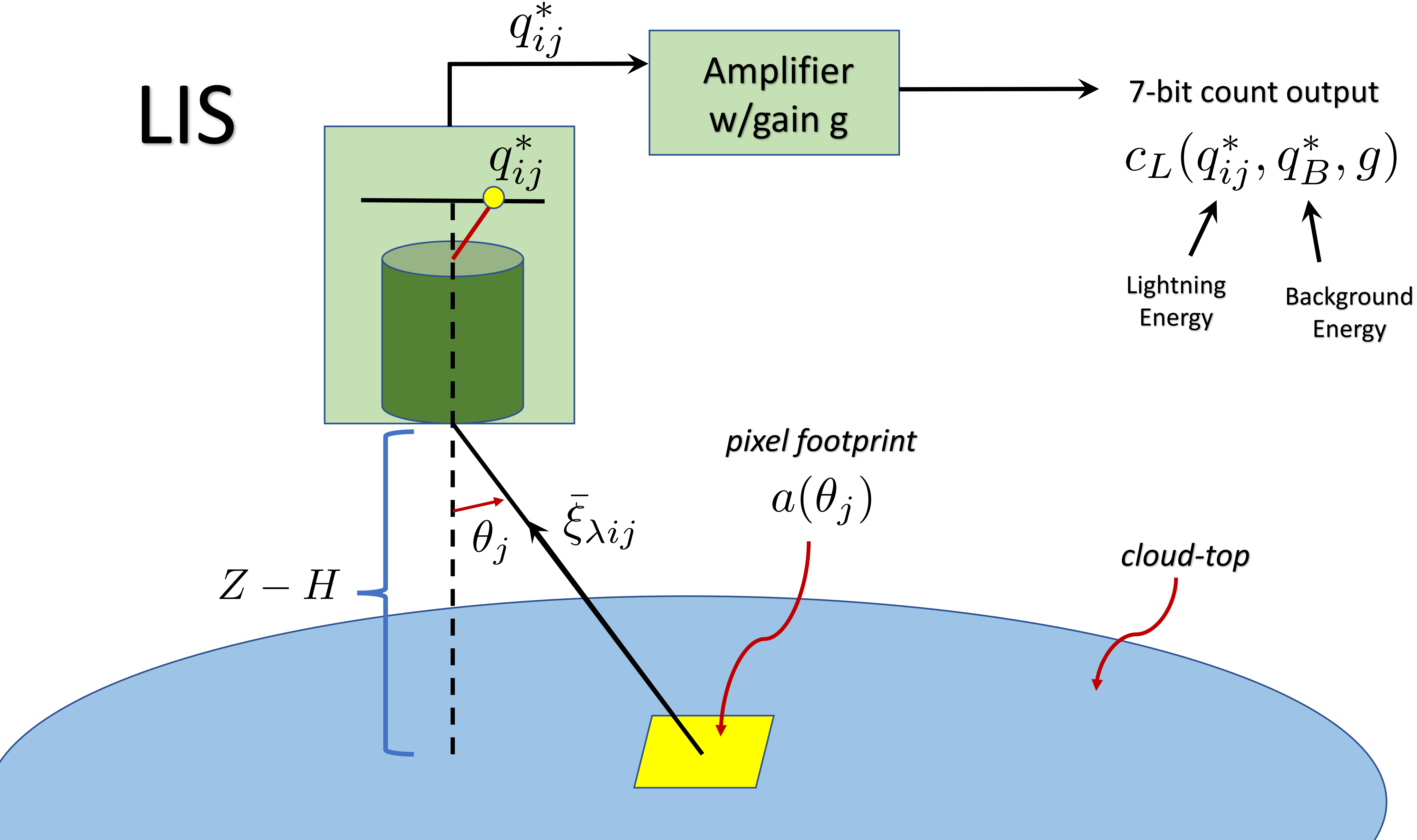
$j = 1, ..., n$ ($n =$ # pixels illuminated by the flash $\neq$ # of EVENTS!, in general)

$\xi_{\lambda i}(\hat{\Omega}) \equiv \int_{t_{i-1}}^{t_i} I_\lambda(\hat{\Omega},t)dt$ = spectral energy density function in i^{th} frame

$\bar{\xi}_{\lambda ij} \equiv \frac{1}{\Delta\omega_j}\int_{\Delta\omega_j}\xi_{\lambda i}(\hat{\Omega})d\Omega$ = mean spectral energy density heading toward j^{th} pixel in i^{th} frame

$\Delta\Omega = \sum_{j=1}^{n}\Delta\omega_j = n\Delta\omega =$ flash solid angle; $\Delta\omega \equiv \frac{1}{n}\sum_{j=1}^{n}\Delta\omega_j =$ mean pixel solid angle in the flash

LIS



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$$q_{ij}^{*} = \int_{t_{i-1}}^{t_i} \int_{\Delta\omega_j} \left[\varepsilon(\hat{\Omega})\tau(\hat{\Omega})A(\hat{\Omega})b(\hat{\Omega})\right] I_\lambda(\hat{\Omega},t)\,d\Omega dt = \int_{t_{i-1}}^{t_i} \int_{\Delta\omega_j} K(\hat{\Omega}) I_\lambda(\hat{\Omega},t)\,d\Omega dt$$

$$= \int_{\Delta\omega_j} K(\hat{\Omega}) \left[\int_{i-1}^{t_i} I_\lambda(\hat{\Omega},t)\,dt\right] d\Omega = \int_{\Delta\omega_j} K(\hat{\Omega}) \xi_{\lambda i}(\hat{\Omega})\,d\Omega \cong K(\hat{\Omega}_j) \int_{\Delta\omega_j} \xi_{\lambda i}(\hat{\Omega})\,d\Omega$$

But,

$$\bar{\xi}_{\lambda ij} \equiv \frac{1}{\Delta\omega_j} \int_{\Delta\omega_j} \xi_{\lambda i}(\hat{\Omega})\,d\Omega$$

Hence,

$$\boxed{q_{ij}^{*} \cong K(\hat{\Omega}_j)\Delta\omega_j \bar{\xi}_{\lambda ij}}$$

Energy Ingested by Pixel (in μJ)

where:

$$\left.\begin{aligned} K(\hat{\Omega}_j) &= K(\hat{\Omega}(\theta_j,\varphi_j)) = K(\theta_j,\varphi_j) \cong K(\theta_j) \\ \Delta\omega_j &= \Delta\omega(\hat{\Omega}(\theta_j,\varphi_j)) = \Delta\omega(\theta_j,\varphi_j) \cong \Delta\omega(\theta_j) \end{aligned}\right\} \text{Azimuthal Symmetry Assumed}$$

$\hat{\Omega}_j = \hat{\Omega}(\theta_j,\varphi_j)$

$\varepsilon(\hat{\Omega})$ = pixel quantum efficiency

$\tau(\hat{\Omega})$ = lens system transmission (i.e., there exists absorption & reflection)

$A(\hat{\Omega})$ = entrance pupil area

$b(\hat{\Omega})$ = filter bandwidth

But, the DC count output for pixel energy q^*_{ij} [units of μJ] is:

$$C_{ij} = G_l q^*_{ij} + y_l$$

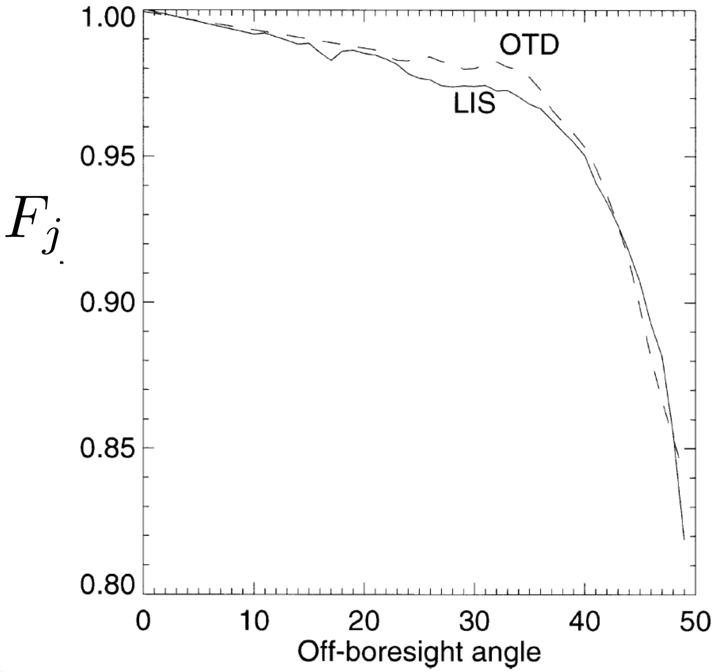
where:

$$G_l = \text{DC gain of the } l^{th} \text{ quadrant; } l = 1, 2, 3, 4$$

$$y_l = \text{DC offset of the } l^{th} \text{ quadrant}$$

So variation F_j in energy ingested by pixel relative to boresight $\theta_0 = 0$ is :

$$F_j = F(\theta_j) \equiv \frac{q^*_{ij}}{q^*_{i0}} = \frac{C_{ij} - y_l}{C_{i0} - y_l} \cong \frac{C_{ij}}{C_{i0}}$$

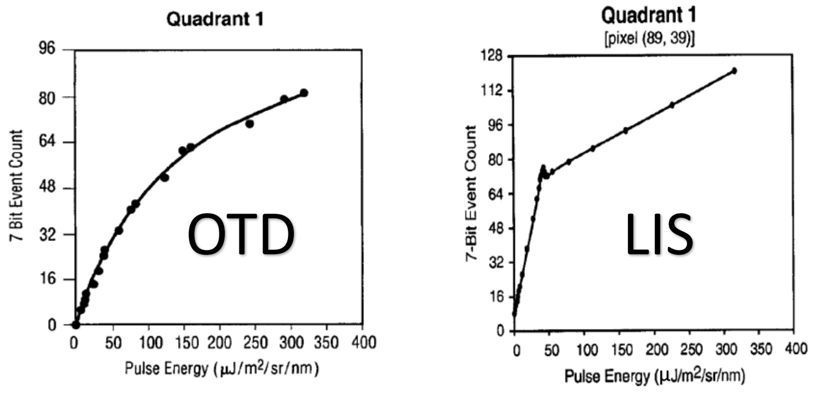


Boccippio, D. J., W. J. Koshak, R. J. Blakeslee, Performance assessment of the Optical Transient Detector and Lightning Imaging Sensor. Part I: predicted diurnal variability, J. Atmos. Oceanic Technol., 19, 1318-1332, 2002.

OTD/LIS Flash Radiance Data Product:

$$\Phi_\lambda \equiv \sum_{i=1}^{m} \sum_{j=1}^{n} \zeta_{\lambda ij}(c)$$

(in $\mu J\ m^{-2} sr^{-1} \mu m^{-1}$)



Koshak, W. J., M. F. Stewart, H. J. Christian, J. W. Bergstrom, J. M. Hall, and R. J. Solakiewicz, Laboratory Calibration of the Optical Transient Detector and the Lightning Imaging Sensor, J. Atmos. Oceanic Technol., 17, 905-915, 2000.

where c is the OTD or LIS 7 - bit count output.

By correcting the HDF data product $\zeta_{\lambda ij}(c_L)$, one can estimate the true incidence:

$$\bar{\xi}_{\lambda ij} \cong \frac{0.985\zeta_{\lambda ij}(c_L)}{F_j}$$

So put all the pieces together:

$$\left\langle \xi_\lambda(\hat{\Omega}) \right\rangle \simeq \frac{1}{n}\sum_{i=1}^{m}\sum_{j=1}^{n}\bar{\xi}_{\lambda ij} \quad \simeq \quad \frac{1}{n}\sum_{i=1}^{m}\sum_{j=1}^{n}\frac{0.985\zeta_{\lambda ij}(c_L)}{F_j}$$

$$\Phi_\lambda \equiv \sum_{i=1}^{m}\sum_{j=1}^{n}\zeta_{\lambda ij}(c)$$

But, a flash is fairly localized to one boresight region so that $F_j \simeq \bar{F}$:

$$\left\langle \xi_\lambda(\hat{\Omega}) \right\rangle \quad \simeq \quad \frac{0.985}{n\bar{F}}\sum_{i=1}^{m}\sum_{j=1}^{n}\zeta_{\lambda ij}(c_L) = \frac{0.985}{n\bar{F}}\Phi_\lambda$$

Hence:

$$\boxed{\Phi_\lambda \simeq \frac{n\bar{F}}{0.985}\left\langle \xi_\lambda(\hat{\Omega}) \right\rangle}$$

So data product generally overestimates true incidence by about a factor of n.
At max boresight the correction is n(0.82)/0.985 = 0.832n

n ~ (flash area)/(pixel footprint)

Analysis of OTD & TRMM/LIS Measurements

Summary

Heritage Flash Amplitude Baseline Computed by Koshak Using Raw Data Results from Various Investigators

Raw Data Source	Koshak OTD CONUS 1999-2000 Z = 3 weighting Resolution Model	Koshak OTD CONUS 1999-2000 data weighting Resolution Model	Buechler & Christian LIS GLOBAL 1998-Jul 2001 Pre-boost Resolution Model	Buechler & Christian LIS GLOBAL Sep 2001-2013 Post-boost Resolution Model	Buechler & Christian LIS GLOBAL 1998-Jul 2001 Pre-boost Res: data 22.6 km²	Buechler & Christian LIS GLOBAL Sep 2001-2013 Post-boost Res: data 25.3 km²	Beirle et al. LIS GLOBAL 1998-2012 both Pre- & Post- Res: BC data 24.7 km²
Koshak Computation	79.8	72.8	55.7	57.9	67.9	**59.9**	60.3

- OTD: poor sensitivity, only CONUS stats done, Z estimate … not best to use.
- More data in LIS Post-Boost than in Pre-boost … so Post-Boost better sample size
- Buechler & Christian study has 1 more year of data than the Beirle et al. study, and more specific mean event footprints (since Beirle didn't separate out Pre-boost from Post-boost).
- So best estimate currently is 6th column above (bolded).

$$\left\langle \xi_\lambda(\hat{\Omega}) \right\rangle \sim 60 \frac{\mu J}{m^2 sr\ nm}$$

Metrics

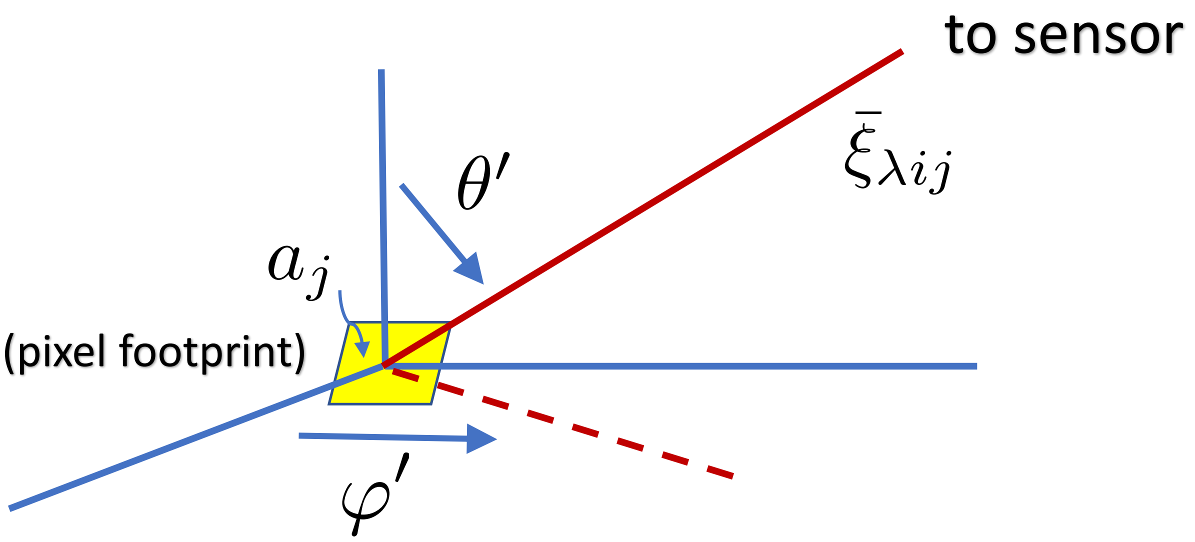
Three Candidates:

$$(1) \qquad Q = \sum_{i=1}^{m}\sum_{j=1}^{n} q_{ij} = \sum_{i=1}^{m}\sum_{j=1}^{n} A_j \Delta\lambda_j \Delta\omega_j \bar{\xi}_{\lambda ij} \qquad (\text{in } \mu J)$$

$$(2) \qquad U_\lambda = \sum_{i=1}^{m}\sum_{j=1}^{n} u_{\lambda ij} = \sum_{i=1}^{m}\sum_{j=1}^{n} \Delta\omega_j \bar{\xi}_{\lambda ij} = \left\langle \xi_\lambda(\hat{\Omega}) \right\rangle \Delta\Omega \qquad (\text{in } \mu J\ m^{-2} nm^{-1})$$

$$(3) \qquad \Gamma_\lambda = \sum_{i=1}^{m}\sum_{j=1}^{n} \gamma_{\lambda ij} = \sum_{i=1}^{m}\sum_{j=1}^{n} \pi \bar{\xi}_{\lambda ij} a_j \qquad (\text{in } \mu J\ nm^{-1})$$

isotropy assumed



$$J_{\lambda ij} = \int_{2\pi} \cos\theta' \bar{\xi}_{\lambda ij} d\Omega' = \bar{\xi}_{\lambda ij} \int_0^{2\pi} \int_0^{\pi/2} \cos\theta' \sin\theta' d\theta' d\varphi'$$

$$\Rightarrow \quad J_{\lambda ij} = \pi \bar{\xi}_{\lambda ij} \quad (\mu J \ m^{-2} nm^{-1})$$ Upward flux density from pixel footprint for i^{th} frame

$$\Rightarrow \quad \Gamma_\lambda = \sum_{i=1}^{m} \sum_{j=1}^{n} J_{\lambda ij} a_j = \sum_{i=1}^{m} \sum_{j=1}^{n} \pi \bar{\xi}_{\lambda ij} a_j$$

Γ_λ is the best Metric

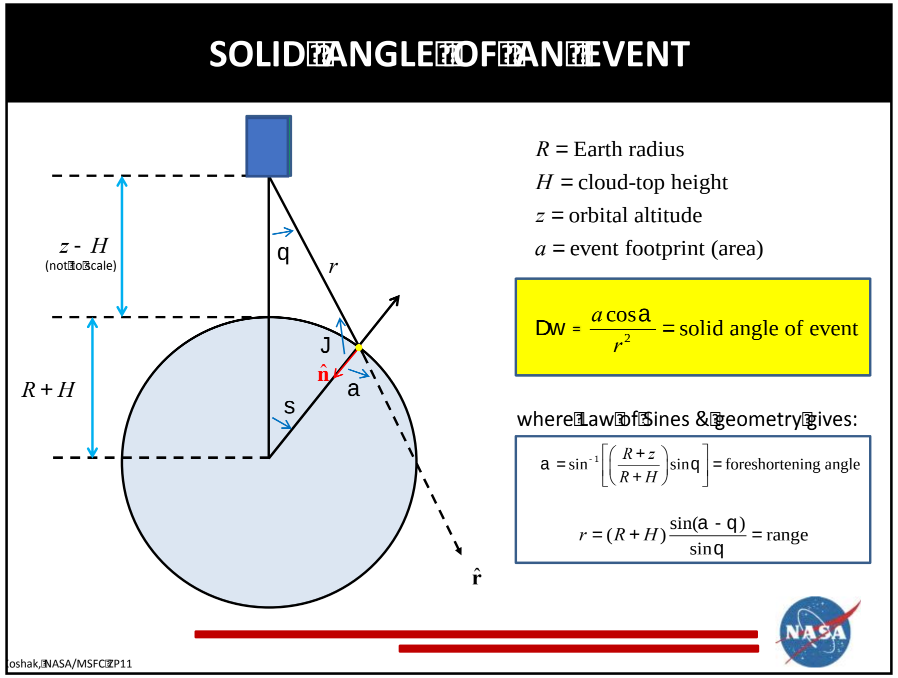
DEPENDENCES	Q	U_λ	Γ_λ
Depends on sensor orbit altitude z ? (i.e. on $\Delta\Omega$?)	YES	YES	NO
Depends on sensor A ?	YES	NO	NO
Depends on sensor $\Delta\lambda$?	YES	NO	NO
Accounts for flash cloud-top area S ?	YES*	YES*	YES

* Bigger $\Delta\Omega \Rightarrow$ bigger S, given z, but flash area is irritatingly modulated by boresight angle.

Comparisons

$$q_{ij} = \bar{\xi}_{\lambda ij} A \Delta\lambda \Delta\omega_j \sim \bar{\xi}_\lambda A \Delta\lambda \left(\frac{a_j \cos \alpha_j}{r_j^2} \right)$$

$$Q = \sum_{i=1}^{m} \sum_{j=1}^{n} q_{ij} = A\Delta\lambda \sum_{i=1}^{m} \sum_{j=1}^{n} \Delta\omega_j \bar{\xi}_{\lambda ij} = \left\langle \xi_\lambda(\hat{\Omega}) \right\rangle A \Delta\lambda \Delta\Omega$$



$a_j = a_j(\theta_j)$ {pixel footprint}

$r_j = (R+z)\cos\theta_j - (R+H)\cos\alpha_j$ {range}

α_j (see above) {foreshortening angle}

$$\bar{\xi}_\lambda \sim 14\ \mu J\ m^{-2} sr^{-1} nm^{-1}, \qquad \left\langle \xi_\lambda(\hat{\Omega}) \right\rangle \sim 60\ \mu J\ m^{-2} sr^{-1} nm^{-1}$$

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$$q = \bar{\xi}_\lambda A \Delta\lambda \Delta\omega$$

$$Q = \left\langle \xi_\lambda(\hat{\Omega}) \right\rangle A \Delta\lambda \Delta\Omega$$

Approximate Energy Ratios [L (LIS Postboost), G (GLM)] at halfway boresight angle:

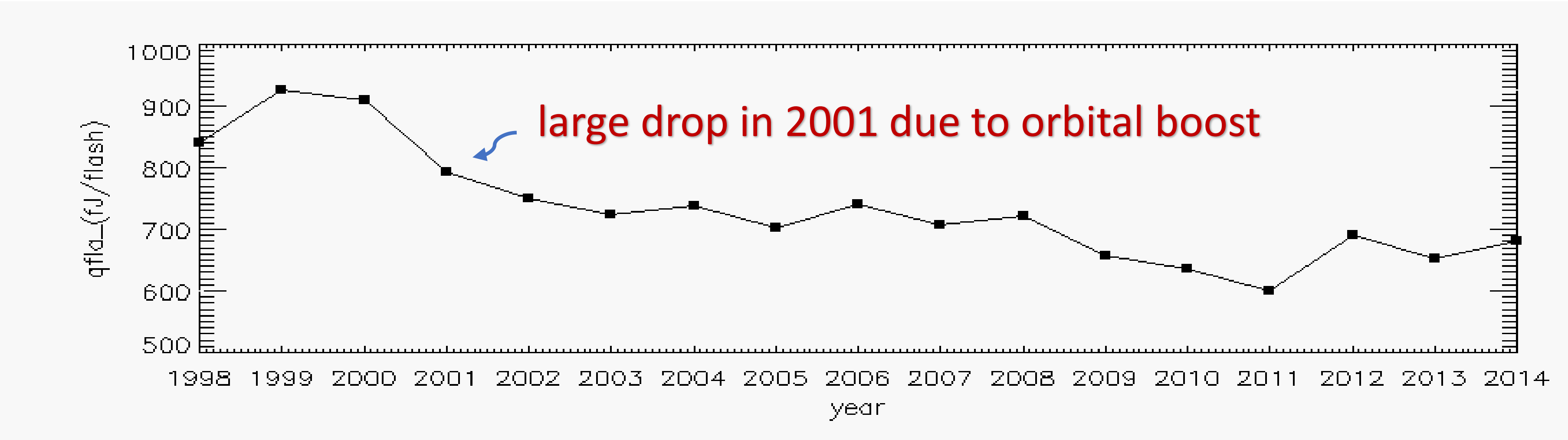
$$\frac{q_L}{q_G} \sim 1.7$$

$$\frac{Q_L}{Q_G} \sim 6.7$$

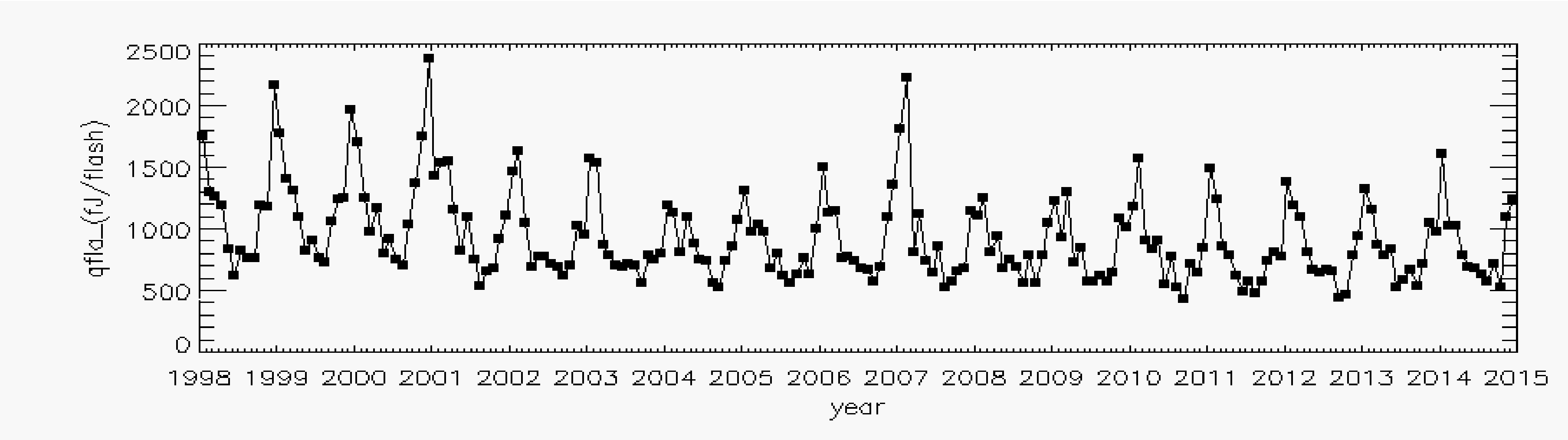
… actual values depend on specific selection of solid angle values, so the 2 ratios can vary.

Trends

TRMM/LIS Incident Flash Optical Energy Q (fJ/flash)



Annual Average



Monthly Average

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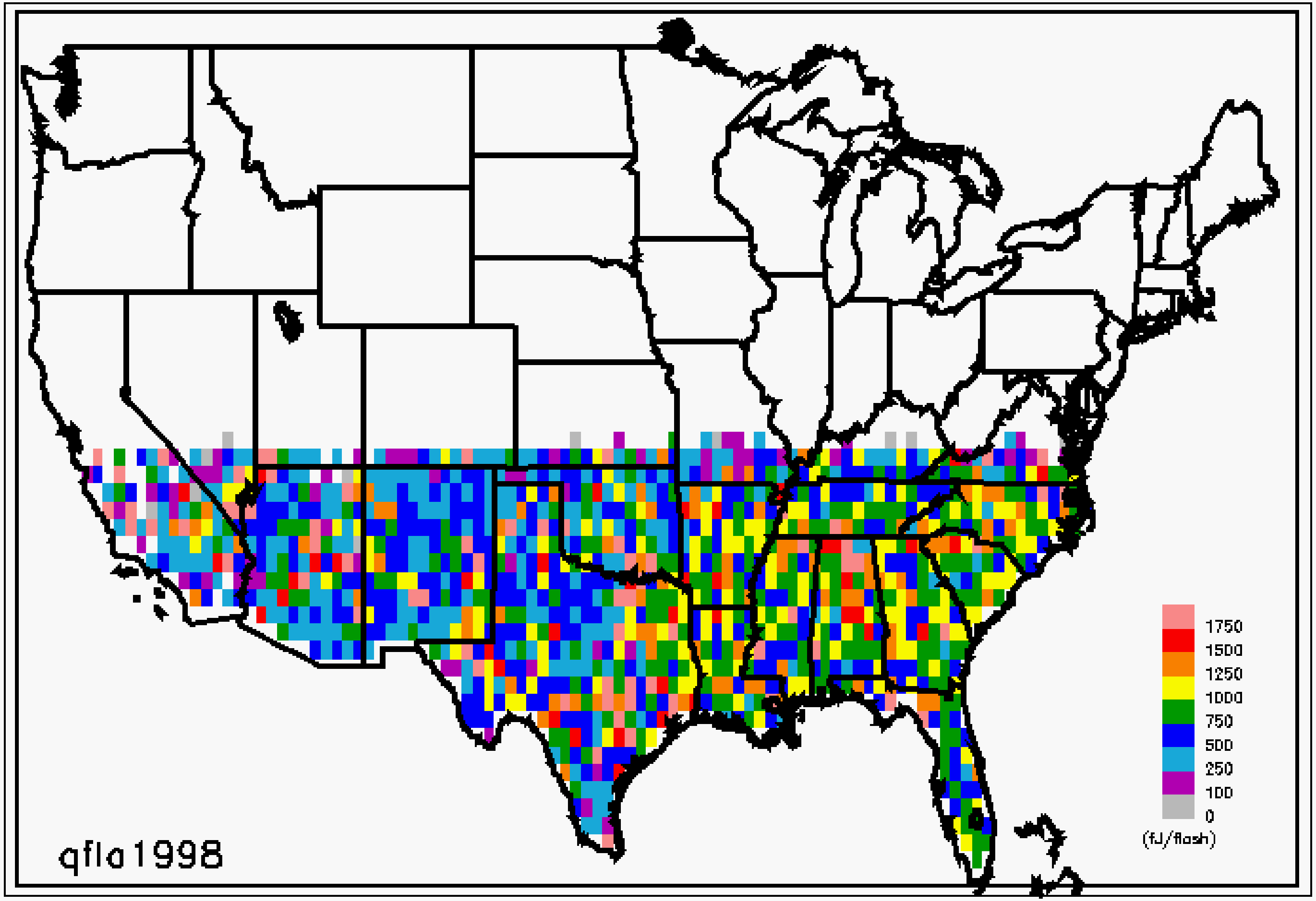

TRMM/LIS Incident Flash Optical Energy Q (fJ/flash)

Annual CONUS values

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